

Studying Photon Structure at Electron-Ion-Collider

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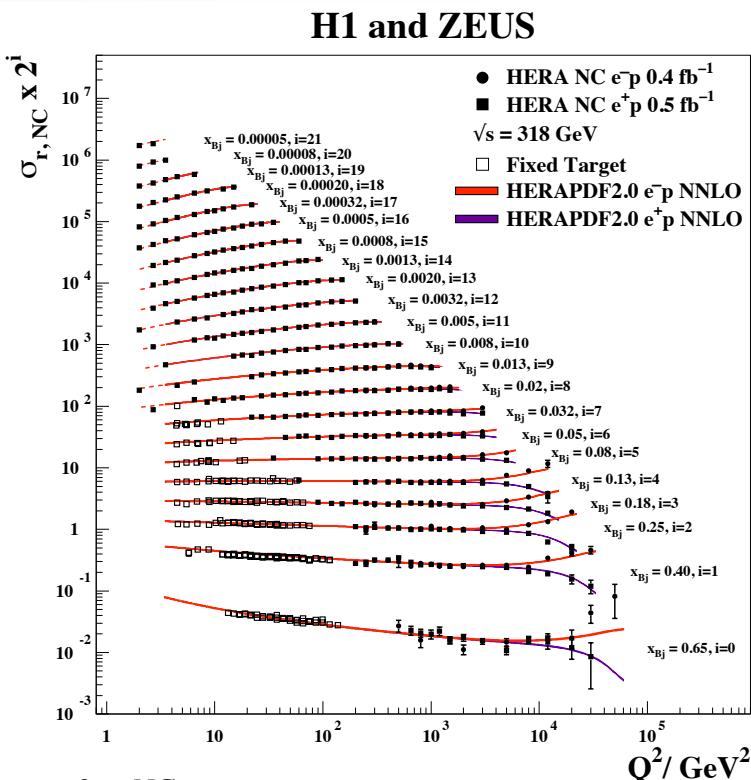
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Outline

- **Introduction**
- **Photon structure at EIC**
 - Di-jet method
 - Validating Monte Carlo with HERA data
 - Separation of direct and resolved process
 - Reconstruct x_γ
 - Jets from photon side & jets from proton side
 - Flavor tagging
- **Summary**

Motivation

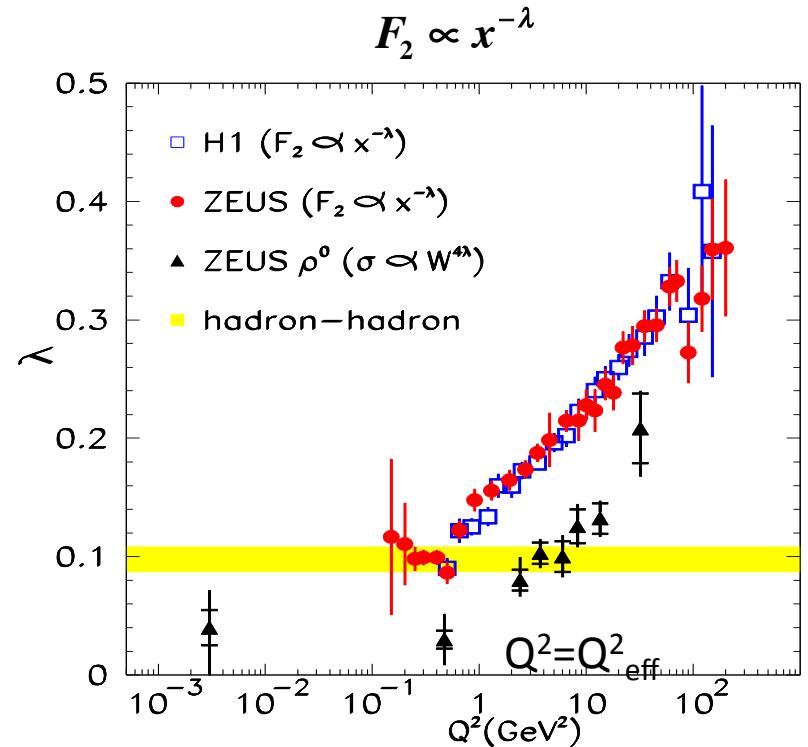


$$\frac{d^2\sigma_{e^\mp p}^{NC}}{dx dQ^2} = \frac{2\pi\alpha_{em}^2 Y_+}{xQ^4} (F_2 - \frac{y^2}{Y_+} F_L \pm \frac{Y_-}{Y_+} x F_3)$$

$q(x, Q^2) - \bar{q}(x, Q^2)$

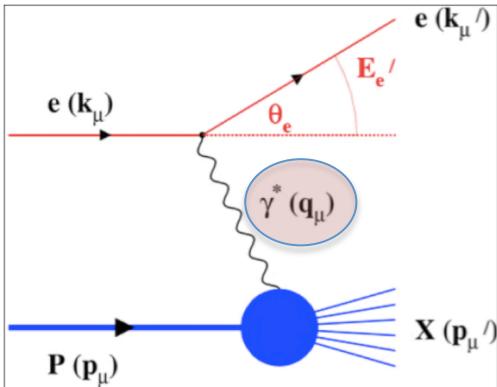
$g(x, Q^2)$

$q(x, Q^2) + \bar{q}(x, Q^2)$

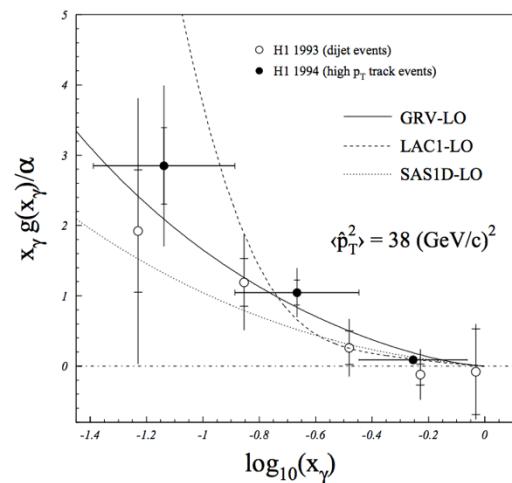


- Structure functions at the same Q^2 for eA and for polarized ep
- Photon structure as fct. of Q^2

Introduction



- Behavior of the exchanged photon: Bare photon state, **Hadronic photon state**
- Photon can be superposition of above states! ($t \approx E / M^2$)
- The “internal structure” of photons is a manifestation of **quantum fluctuations**: Photon splits into parton content
- We measure the photon structure in **photoproduction**: Low Q^2 events

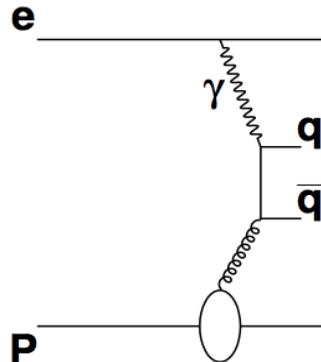


- **Unpolarized photon structure:**
arXiv:9504004, arXiv:9710018, Eur. Phys. J. C 10, 363-372 (1999), DESY 97-164
- **Polarized photon structure:** (critical input for ILC $\gamma\gamma$ option)
Experiment: no data
Theory: Z. Phys. C 74, 641—650 (1997) and arXiv:971125

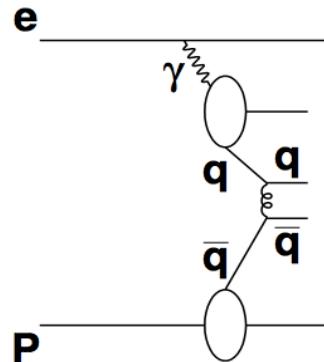
x_γ is defined as the momentum fraction of the parton from the photon

HERA data: gluon density of the photon

Dijet in resolved/direct process

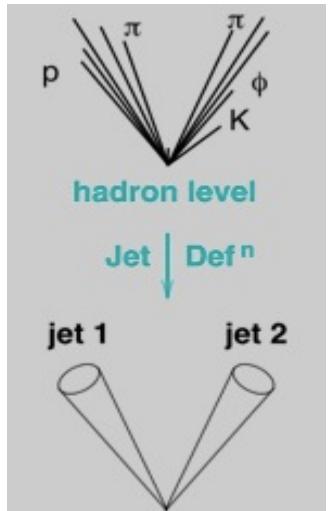


PGF: Di-jet produced



Similar with pp collision

- “**Direct process**” category
 - Point-like photon (no substructure)
 - x_γ is close to 1
- “**Resolved process**” category
 - Hadronic photon
 - x_γ is smaller than 1
 - Di-jet production



- Separate di-jet produced in resolved and direct processes, to get clear resolved process
- Reconstruct x_γ by using di-jet as observables:
 - Two jets with highest p_T
 - Parton densities in the photon can be extracted by measuring **di-jet cross section**

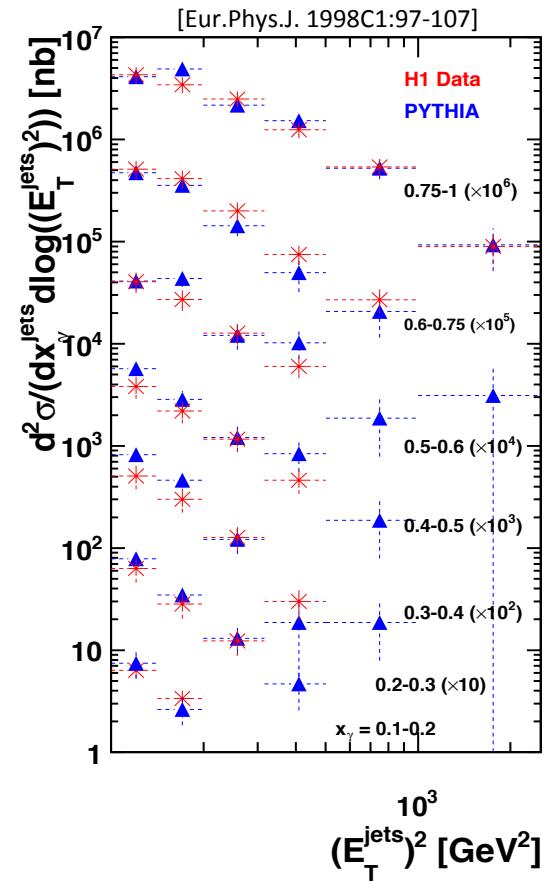
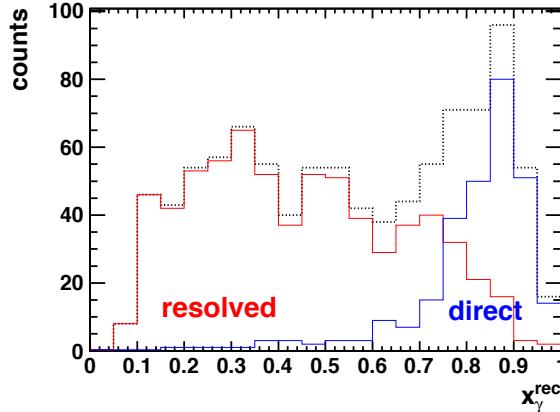
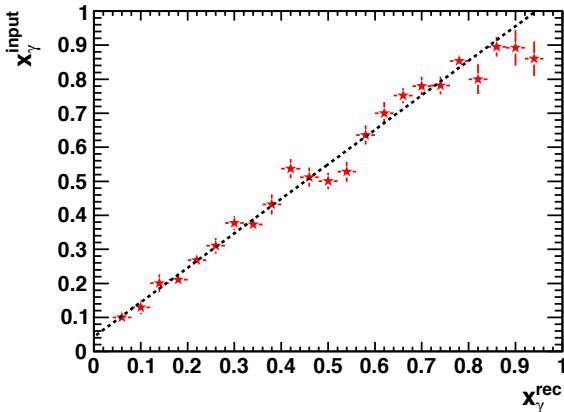
$$x_\gamma^{rec} = \frac{1}{2E_e y} (p_{T1} e^{-\eta_1} + p_{T2} e^{-\eta_2})$$

Simulation confronted with data

Kinematics cuts from HERA:

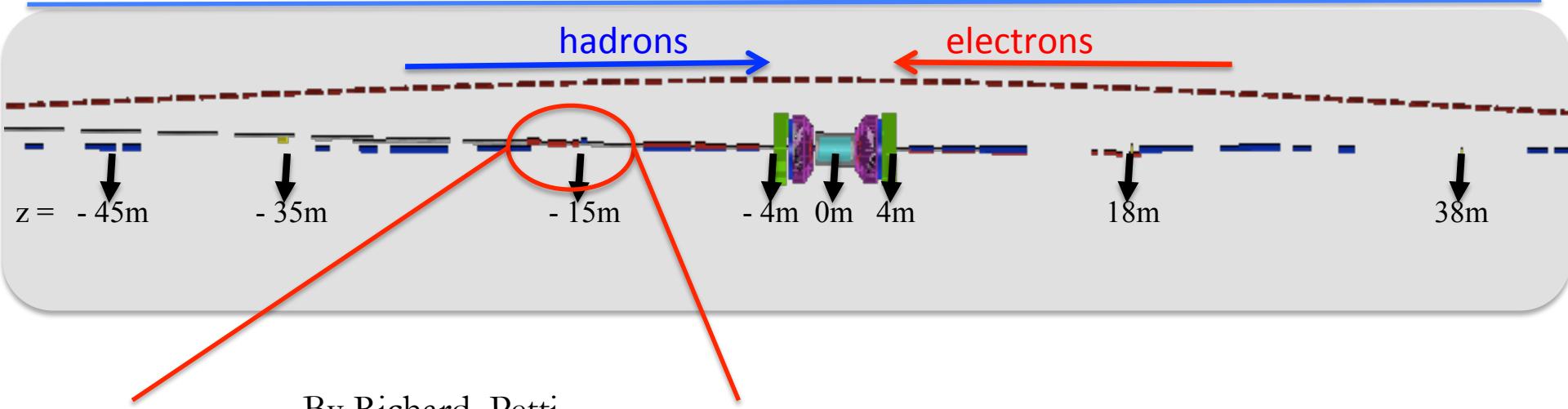
$27.5\text{GeV} \times 820\text{GeV}$, $0.2 < y < 0.83$, $|\Delta \eta_{\text{jets}}| < 1$, $0 < \eta^{\text{jet1}} + \eta^{\text{jet2}} < 4$

$E_{T}^{\text{jet1}}, E_{T}^{\text{jet2}} > 7.5 \text{ GeV}$, $E_{T}^{\text{jet1}} + E_{T}^{\text{jet2}} > 20 \text{ GeV}$, $|E_{T}^{\text{jet1}} - E_{T}^{\text{jet2}}| / (E_{T}^{\text{jet1}} + E_{T}^{\text{jet2}}) < 0.25$

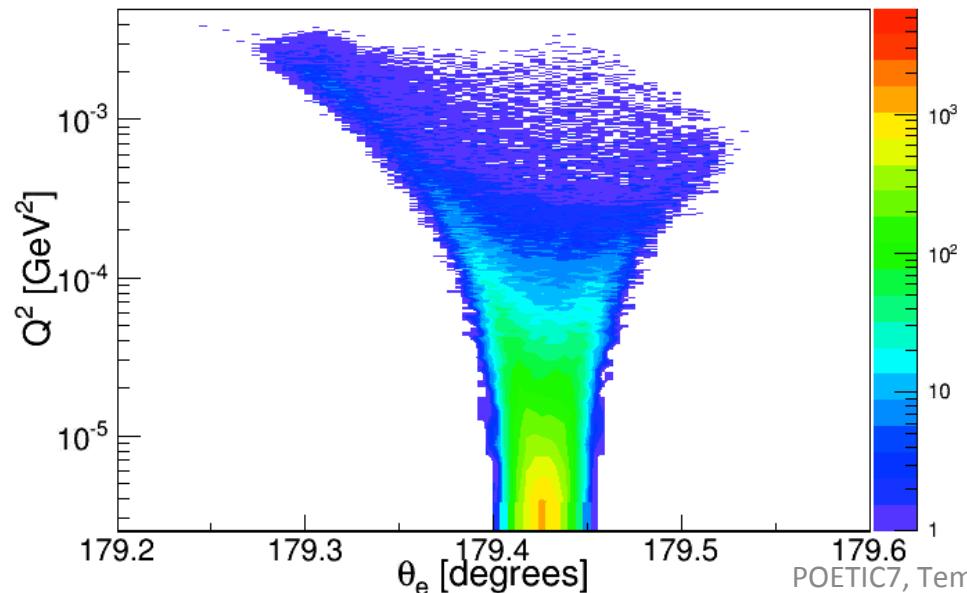


- Strong correlation observed between x_γ^{input} and the input x_γ^{rec} used in the simulation indicates **the di-jet observable** is ideal for x_γ reconstruction
- Reconstructing x_γ^{rec} provides a good way to **separate direct/resolved** contribution ($x_\gamma^{\text{rec}} < 0.75$)
- Our simulation can match the existing data perfectly

EIC Advantages



By Richard. Petti



- pythia events with electron reconstructed in the tagger
- acceptance for electrons down to $Q^2 \sim 1 \times 10^{-5}$ GeV 2

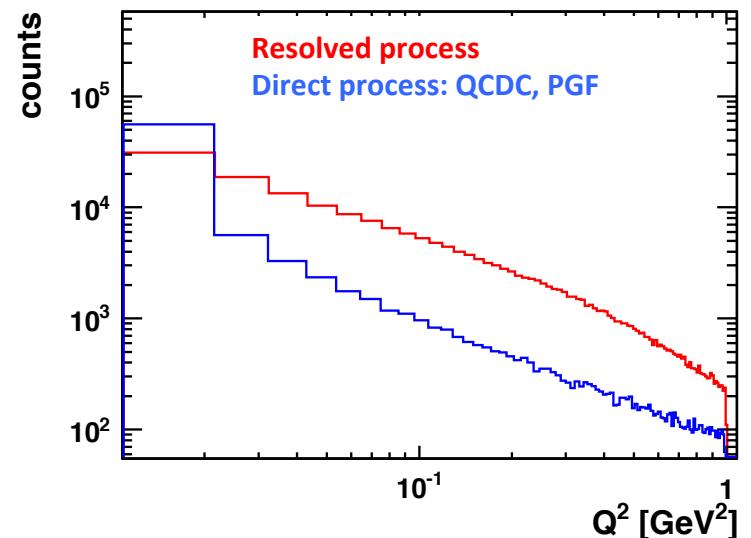
Photon structure at EIC

- Statistic description
 - 1. Basic parameters

Parameter	Set
Ee	20 GeV
Ep	250 GeV
Q^2	< 1
x	$10^{-9} — 0.99$
Proton PDF set	CTEQ5
Photon PDF set	GRV

CTEQ5 shows the best description of cross section at low Q^2

- 2. Di-jet produced in ep collision through hard scattering



Resolved process
 $qq \rightarrow qq$
 $q q\bar{q} \rightarrow q q\bar{q}$
 $q q\bar{q} \rightarrow gg$
 $gq(qg) \rightarrow gq(qg)$
 $gg \rightarrow q q\bar{q}$
 $gg \rightarrow gg$

79%

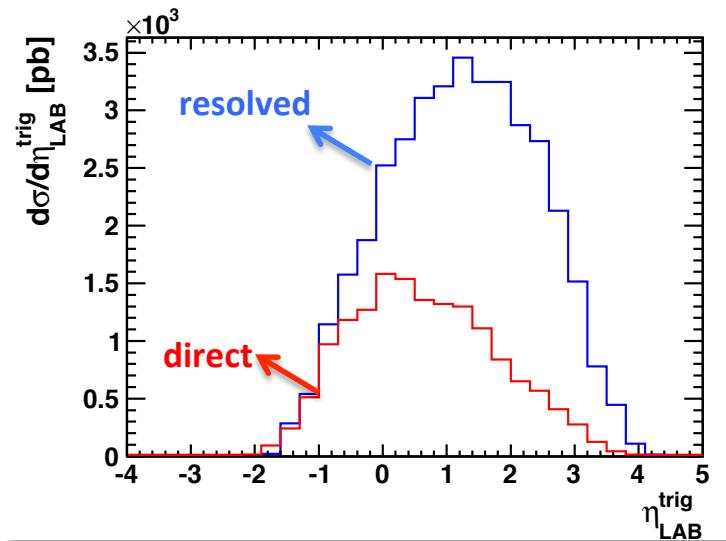
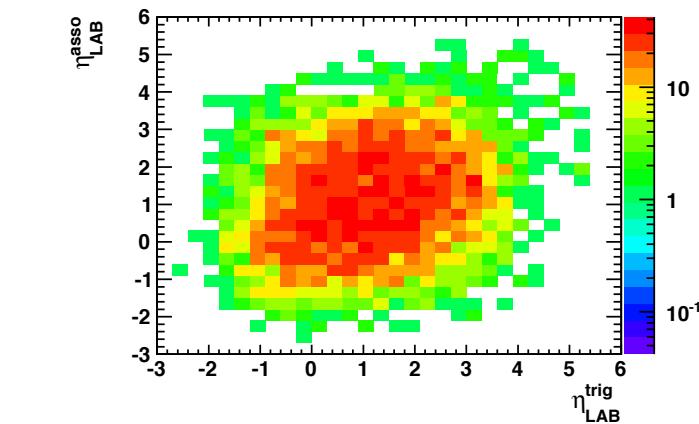
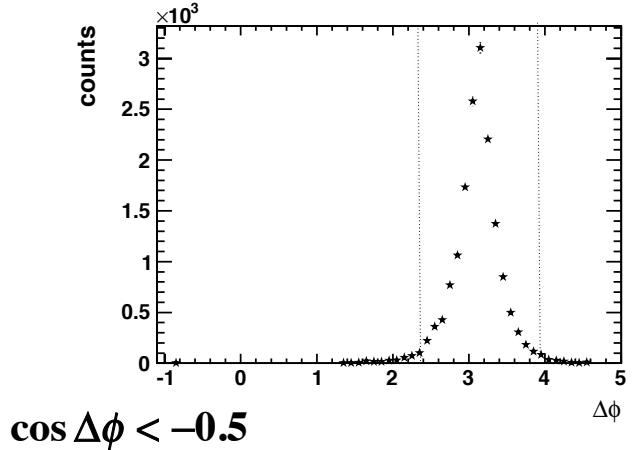
Direct process: QCDC, PGF
 $\gamma_T q \rightarrow qg$
 $\gamma_L q \rightarrow qg$
 $\gamma_T g \rightarrow q q\bar{q}$
 $\gamma_L g \rightarrow q q\bar{q}$

21%

Kinematics cuts for di-jet methods

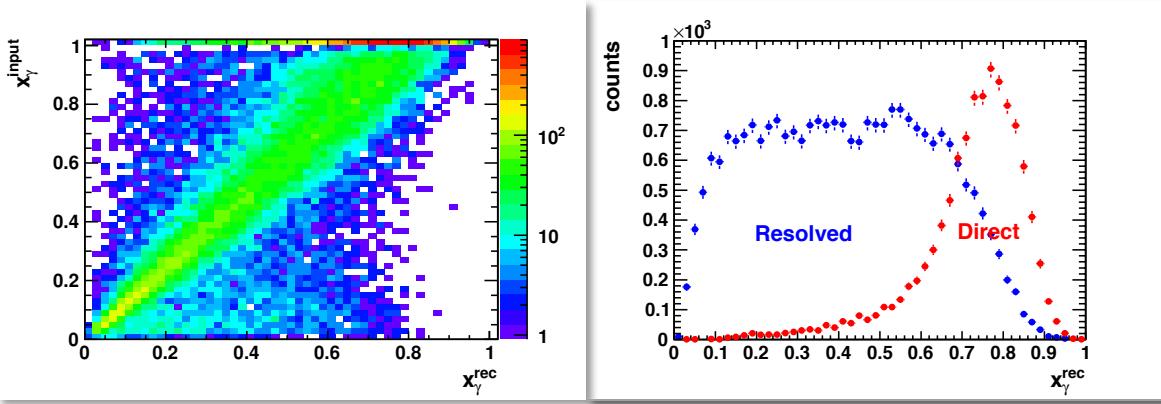
Di-jet cut:

1. Two highest p_T , $p_T^{\text{trig}} > 5 \text{ GeV}$, $p_T^{\text{asso}} > 4.5 \text{ GeV}$
2. Inside the jet, stable particle $p_T > 250 \text{ MeV}$

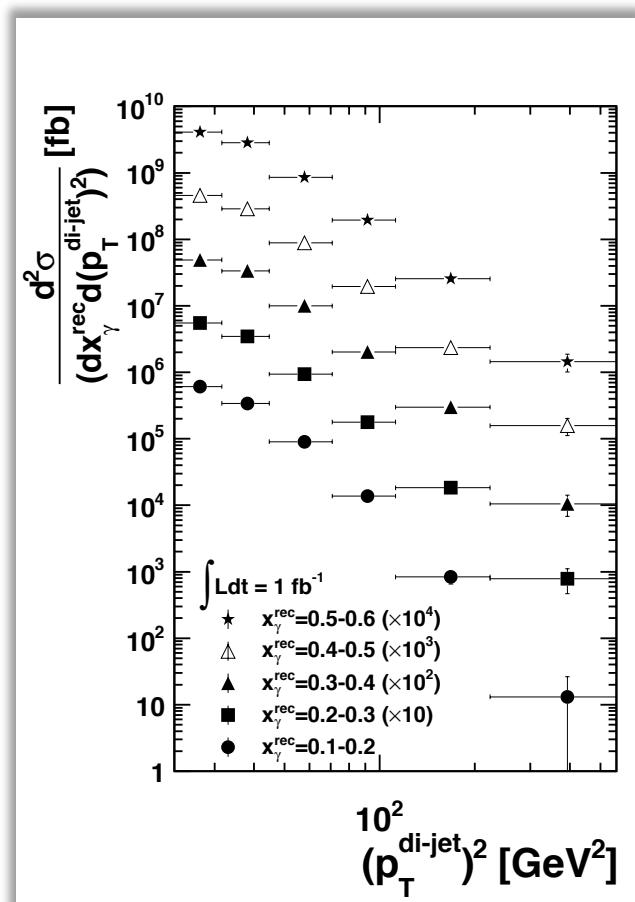


- At positive η_{LAB} , especially $\eta_{\text{LAB}} > 2$, the cross section is dominated by resolved process
- $\eta_{\text{asso,LAB}}$ distribution of associate jet shows the same result

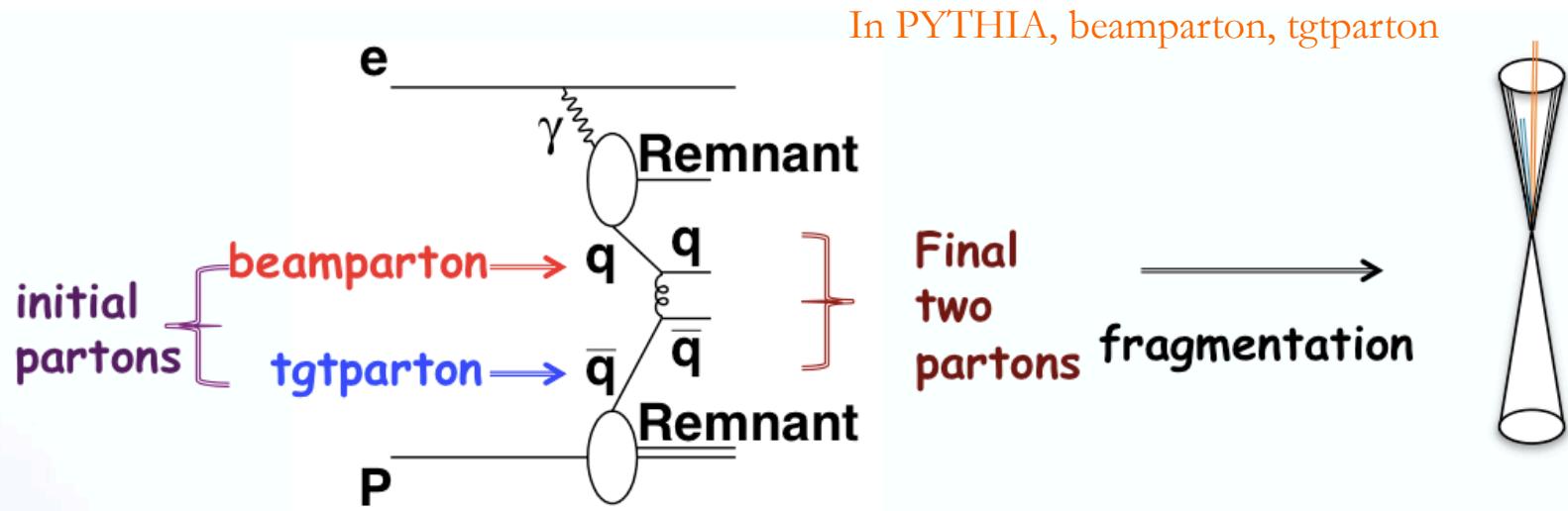
Unpolarized photon structure



- Di-jet method provides a good way to reconstruct x_{γ}^{rec}
- Di-jet method can help us separate resolved/direct process
- The simulation shows the capability to measure the cross section for di-jet production, with high accuracy in a wide kinematic range at EIC and extract the photon PDFs from a global fit

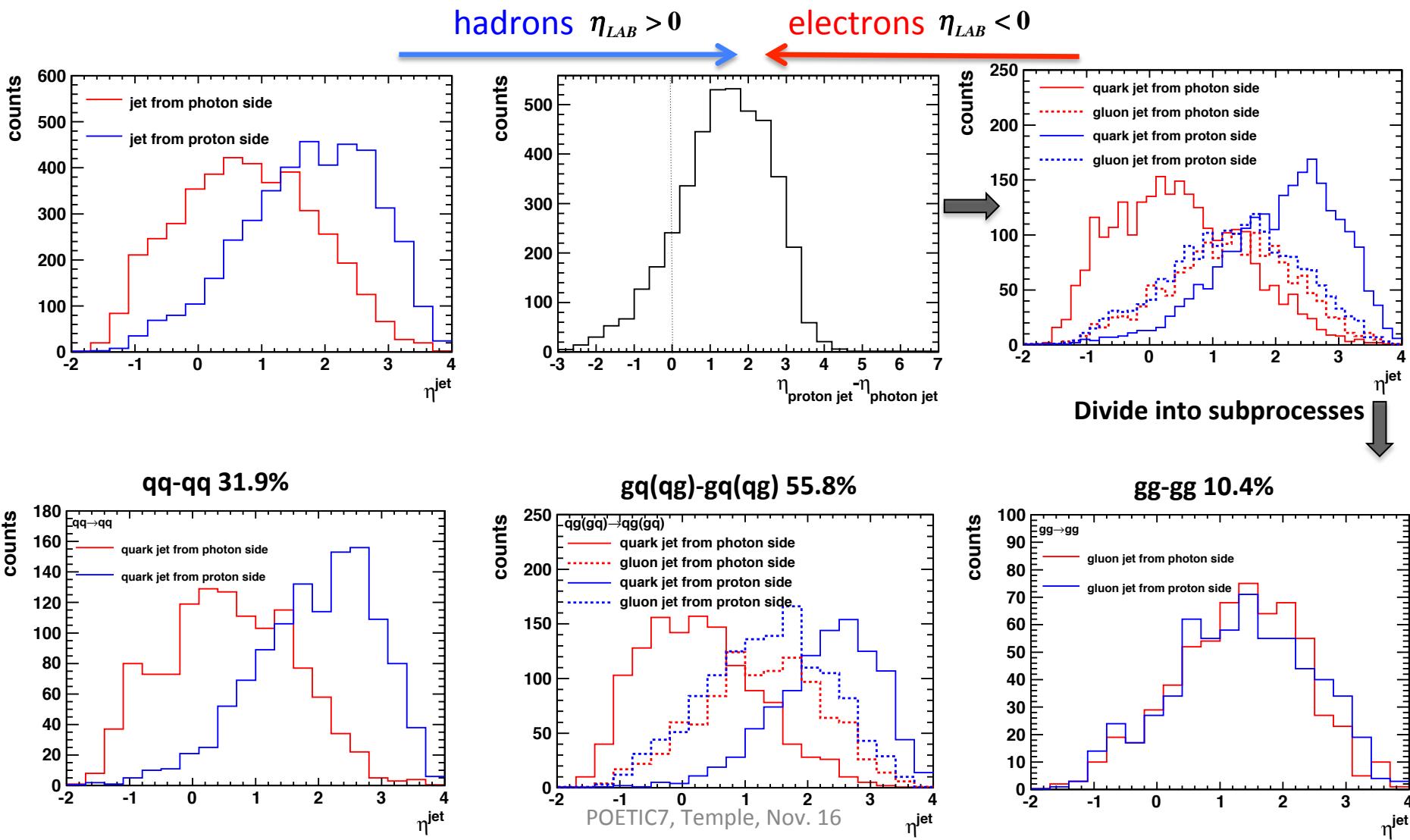


Parton-jet match



- As we have known how to separate “direct” and “resolved” process, then we measure jet kinematics in resolved process
- Basic info about resolved process and how to tag di-jet back to two final partons
- “Path” to do parton-jet match:
 - beamparton - one final parton - one jet of di-jet \implies Jet from photon side
 - tgtparton - another final parton - another jet of di-jet \implies Jet from proton side
- Geometric match $\Delta R\{\text{parton} - \text{jet}\} = \sqrt{\Delta\phi^2 + \Delta y^2}$
 $\Delta E\{\text{parton} - \text{jet}\}$

Photon side jet and proton side jet

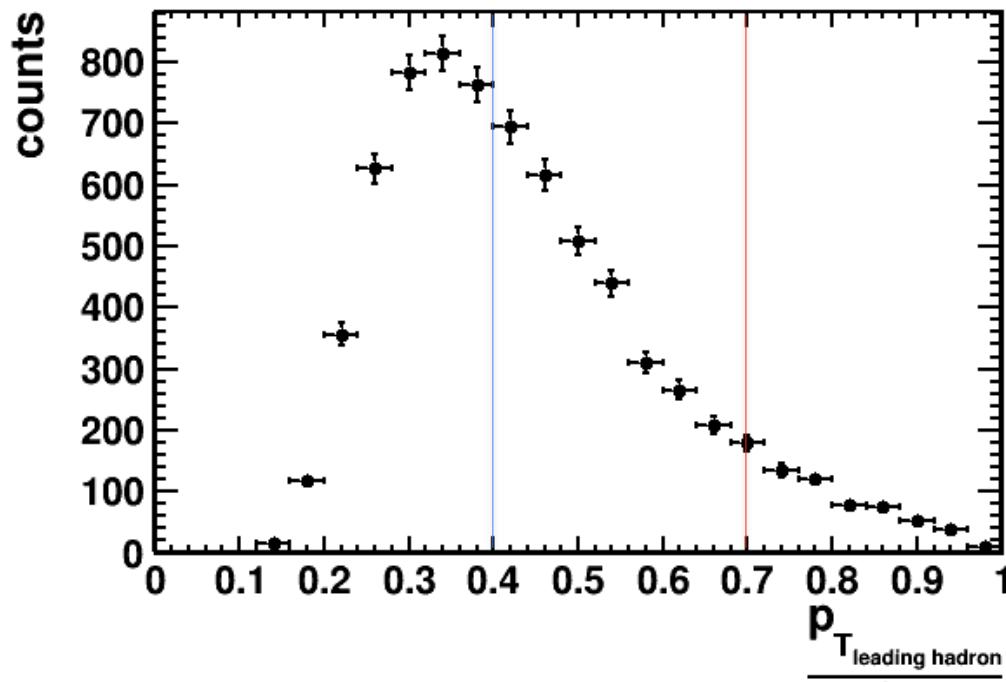


Flavor tagging

Di-jet, trigger jet $p_T > 5$ GeV, associate jet $p_T > 4.5$ GeV



Leading charged hadron inside
Photon side jet



1. p_T fraction: no cut
2. p_T fraction: >0.4
3. p_T fraction: >0.7

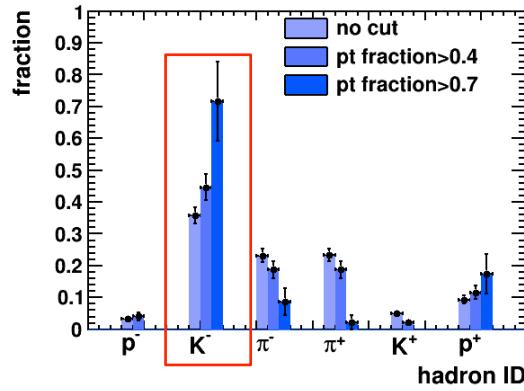
Flavor tagging

Di-jet, trigger jet $\text{pt} > 5 \text{ GeV}$, associate jet $\text{pt} > 4.5 \text{ GeV}$

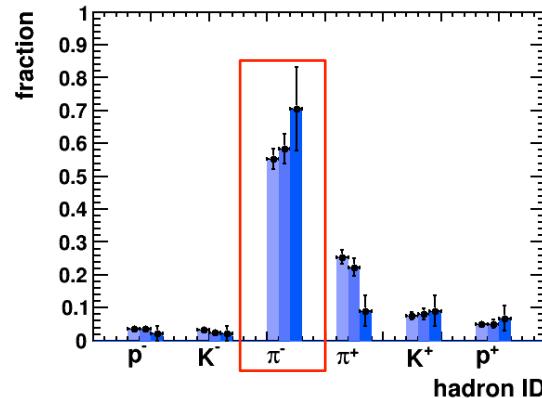


Leading charged hadron inside
Photon side jet

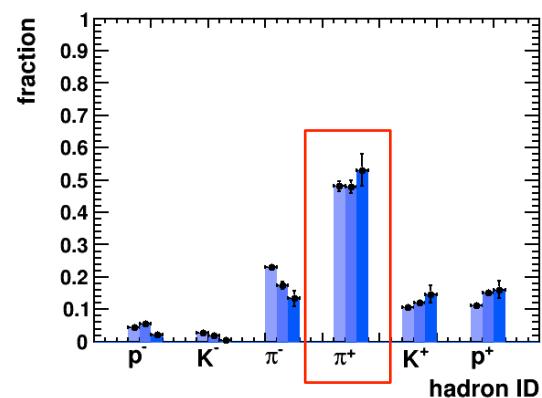
Beamparton is **s** quark



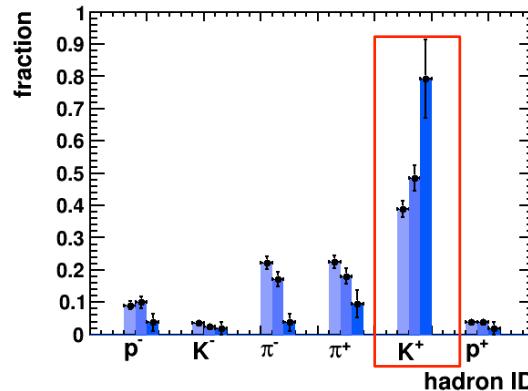
Beamparton is **d** quark



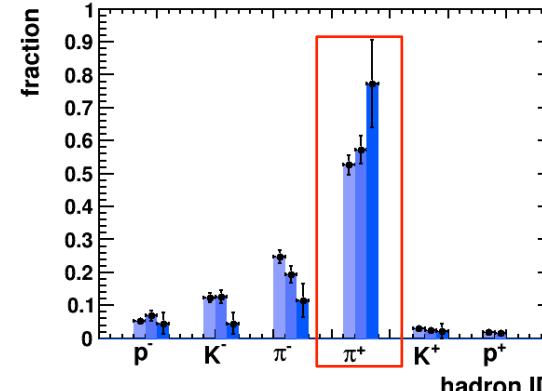
Beamparton is **u** quark



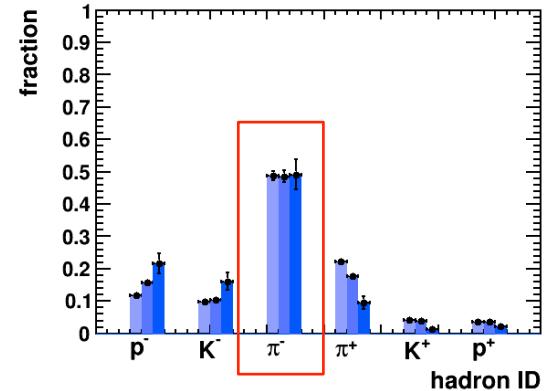
Beamparton is **sbar** quark



Beamparton is **dbar** quark



Beamparton is **ubar** quark



Polarized photon PDFs

Polarized photon PDFs

Based on the unpolarized data from PYTHIA, we add a weight on an event-by-event basis just in analysis code to make it polarized.

- In resolved process, For each event, $\text{ab} \rightarrow \text{cd}$ process, the weight is calculated as:

$$w = \hat{a}(\hat{s}, \hat{t}, \hat{\mu}^2, Q^2) \cdot \frac{\Delta f_a^{\gamma^*}(x_a, \mu^2)}{f_a^{\gamma^*}(x_a, \mu^2)} \cdot \frac{\Delta f_b^N(x_b, \mu^2)}{f_b^N(x_b, \mu^2)}$$
$$\hat{a}(\hat{s}, \hat{t}, \hat{\mu}^2) = \Delta\hat{\sigma}/(2\hat{\sigma})$$

the input pol photon and proton PDFs, we can get **delta_f**

Hard subprocess asymmetry depending on the type of the 2-2 process, the parton kinematics described by Mandelstam variables and photon virtuality.

Unpol photon PDFs and **Unpol proton PDFs**, from **LHAPDF** to get the unpol photon PDFs

Histogram ->Fill(variable, weight)

PYTHIA simulation

$$w = \hat{a}(\hat{s}, \hat{t}, \hat{\mu}^2, Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a, \mu^2)}{f_a^{\gamma^*}(x_a, \mu^2)} \bullet \frac{\Delta f_b^N(x_b, \mu^2)}{f_b^N(x_b, \mu^2)}$$

PYTHIA Input Set	
Q^2	$10^{-5} - 1$
Proton PDFs	CTEQ 5M
Photon PDFs	GRV-NLO

Polarized photon PDF(delta f_a)	
Minimal polarization	$\Delta f_a^{\gamma^*}(x_a, \mu^2) = 0$
Maximal polarization	$\Delta f_a^{\gamma^*}(x_a, \mu^2) = f_a^{\gamma^*}(x_a, \mu^2)$

Polarized proton PDF(delta f_b)	DSSV
UnPolarized photon PDF(f_a)	LHAPDF CTEQ 5m
UnPolarized proton PDF(f_b)	LHAPDF GRV-NLO

Hard process Asymmetry \hat{a}

$$w = \hat{a}(\hat{s}, \hat{t}, \hat{u}, \mu^2, Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a, \mu^2)}{f_a^{\gamma^*}(x_a, \mu^2)} \bullet \frac{\Delta f_b^N(x_b, \mu^2)}{f_b^N(x_b, \mu^2)}$$

Reaction	$d\hat{\sigma}/d\hat{t}$	$d\Delta\hat{\sigma}/d\hat{t}$
$qg \rightarrow qg$	$(\hat{s}^2 + \hat{u}^2)[\frac{1}{\hat{t}^2} - \frac{4}{9\hat{s}\hat{u}}]$	$2(\hat{u}^2 - \hat{s}^2)[\frac{4}{9\hat{s}\hat{u}} - \frac{1}{\hat{t}^2}]$
$\bar{q}g \rightarrow \bar{q}g$	$(\hat{s}^2 + \hat{u}^2)[\frac{1}{\hat{t}^2} - \frac{4}{9\hat{s}\hat{u}}]$	$2(\hat{u}^2 - \hat{s}^2)[\frac{4}{9\hat{u}\hat{s}} - \frac{1}{\hat{t}^2}]$
$gg \rightarrow q\bar{q}$	$\frac{\hat{u}^2 + \hat{t}^2}{6\hat{u}\hat{t}} - \frac{3}{8} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}$	$\frac{3}{4} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} - \frac{\hat{u}^2 + \hat{t}^2}{3\hat{u}\hat{t}}$
$gg \rightarrow gg$	$\frac{9}{2}(3 - \frac{\hat{t}\hat{u}}{\hat{s}^2} - \frac{\hat{s}\hat{u}}{\hat{t}^2} - \frac{\hat{s}\hat{t}}{\hat{u}^2})$	$9(-3 + 2\frac{\hat{s}^2}{\hat{u}\hat{t}} + \frac{\hat{u}\hat{t}}{\hat{s}^2})$
$qaqb \rightarrow qaqb$	$\frac{4}{9}[\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \delta_{ab}(\frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} - \frac{2\hat{s}^2}{3\hat{t}\hat{u}})]$	$\frac{8}{9}[\frac{\hat{s}^2 - \hat{u}^2}{\hat{t}^2} - \delta_{ab}(\frac{\hat{t}^2 - \hat{s}^2}{\hat{u}^2} + \frac{2\hat{s}^2}{3\hat{t}\hat{u}})]$
$qa\bar{q}b \rightarrow qc\bar{q}d$	$\frac{4}{9}[\delta_{ac}\delta_{bd}\frac{\hat{u}^2}{\hat{t}^2} + \delta_{cd}\delta_{ab}\frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} - \delta_{ad}\delta_{cd}\frac{2\hat{u}^2}{3\hat{s}\hat{t}} + \delta_{ab}\delta_{bd}\frac{\hat{s}^2}{\hat{t}^2}]$	$\frac{8}{9}[-\delta_{ac}\delta_{bd}\frac{\hat{u}^2}{\hat{t}^2} - \delta_{cd}\delta_{ab}\frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} + \delta_{ad}\delta_{cd}\frac{2\hat{u}^2}{3\hat{s}\hat{t}} + \delta_{ab}\delta_{bd}\frac{\hat{s}^2}{\hat{t}^2}]$
$q\bar{q} \rightarrow gg$	$\frac{32}{27} \frac{\hat{t}^2 + \hat{u}^2}{\hat{u}\hat{t}} - \frac{8}{3} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}$	$-\frac{64}{27} \frac{\hat{t}^2 + \hat{u}^2}{\hat{u}\hat{t}} + \frac{16}{3} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}$

$$\hat{a}(\hat{s}, \hat{t}, \hat{u}, \mu^2) = \Delta \hat{\sigma} / (2 \hat{\sigma}) \quad [10.1007/JHEP08(2010)130]$$

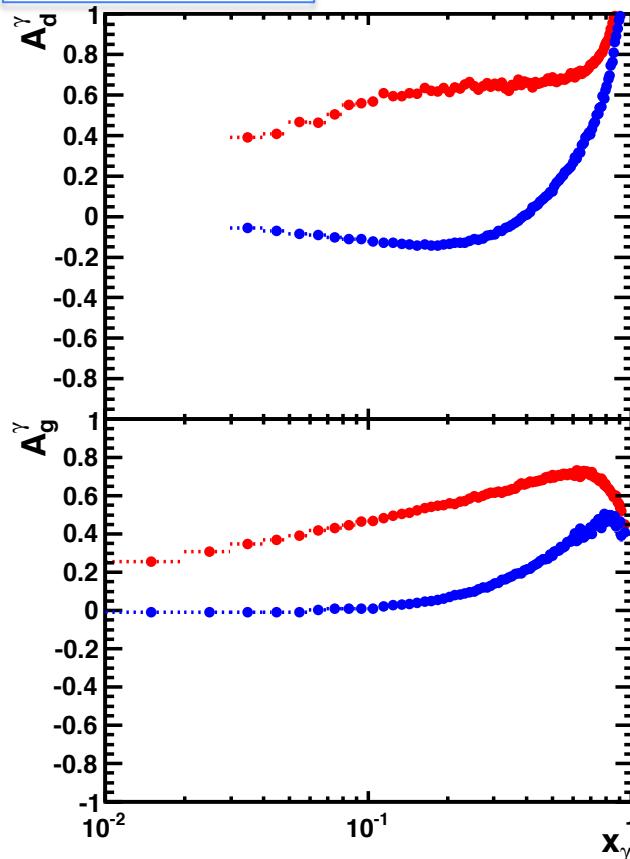
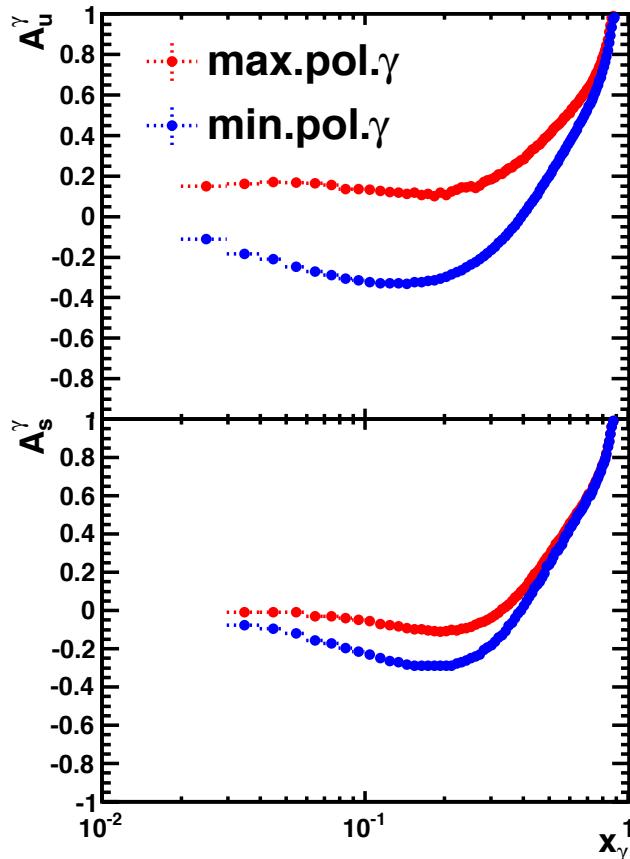
$$\hat{s} = (p_a + p_b)^2, \hat{t} = (p_a - p_c)^2, \hat{u} = (p_a - p_d)^2$$

$$\frac{\Delta f_a^{\gamma^*}(x_a, \mu^2)}{f_a^{\gamma^*}(x_a, \mu^2)}$$

Depending on flavor

$$w = \hat{a}(\hat{s}, \hat{t}, \hat{\mu}^2, Q^2) \bullet$$

$$\frac{\Delta f_a^{\gamma^*}(x_a, \mu^2)}{f_a^{\gamma^*}(x_a, \mu^2)} \bullet \frac{\Delta f_b^N(x_b, \mu^2)}{f_b^N(x_b, \mu^2)}$$



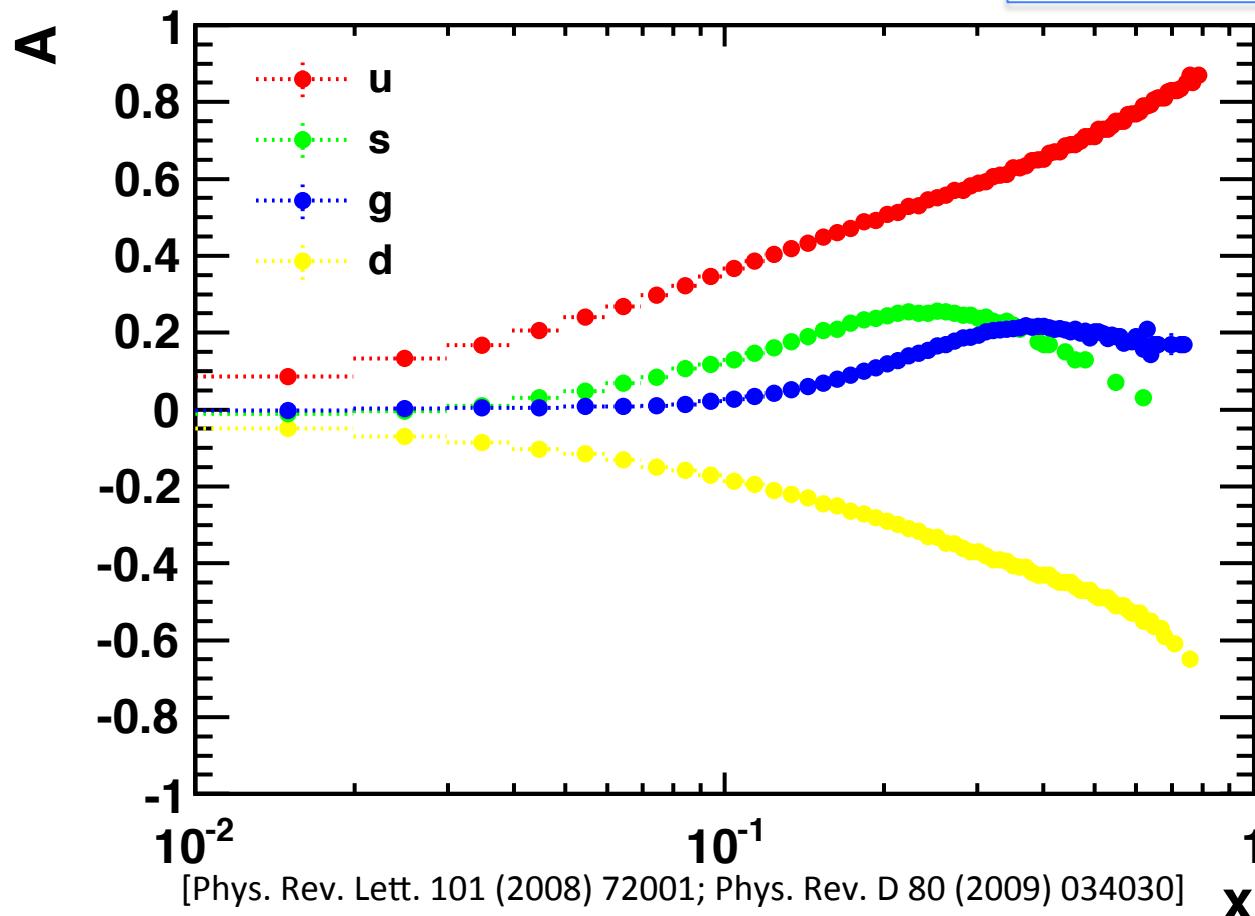
[Z. Phys. C55 (1992) 353; C57 (1993) 309; Phys. Lett. B337 (1994) 373; Phys. Lett. B386 (1996) 370]

POETIC7, Temple, Nov. 16

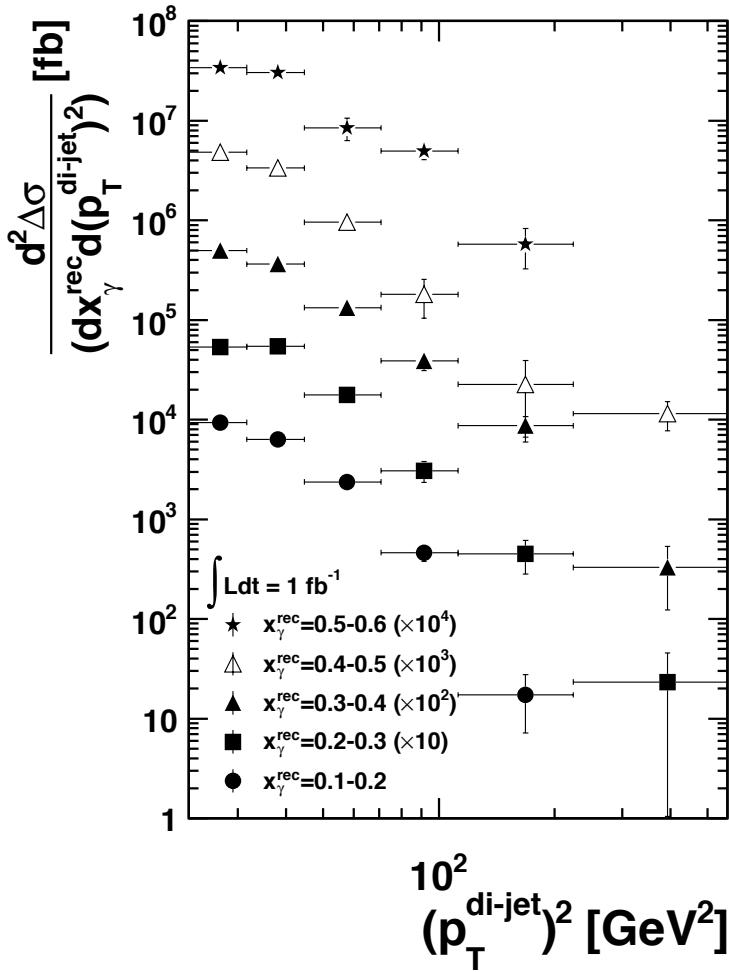
$$\frac{\Delta f_a^{\gamma^*}(x_a, \mu^2)}{f_a^{\gamma^*}(x_a, \mu^2)}$$

Depending on flavor

$$w = \hat{a}(\hat{s}, \hat{t}, \mu^2, Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a, \mu^2)}{f_a^{\gamma^*}(x_a, \mu^2)} \bullet \frac{\Delta f_b^N(x_b, \mu^2)}{f_b^N(x_b, \mu^2)}$$



Polarized cross section



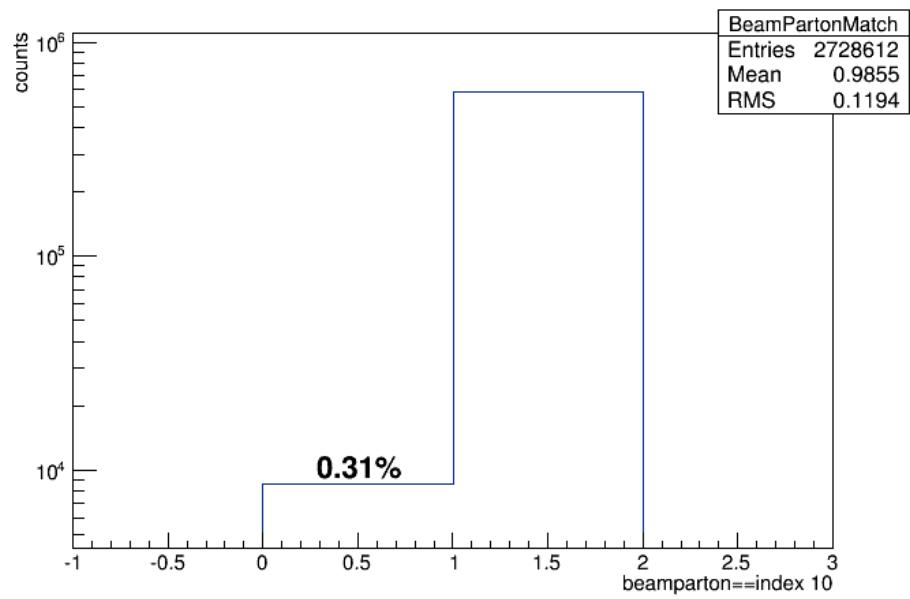
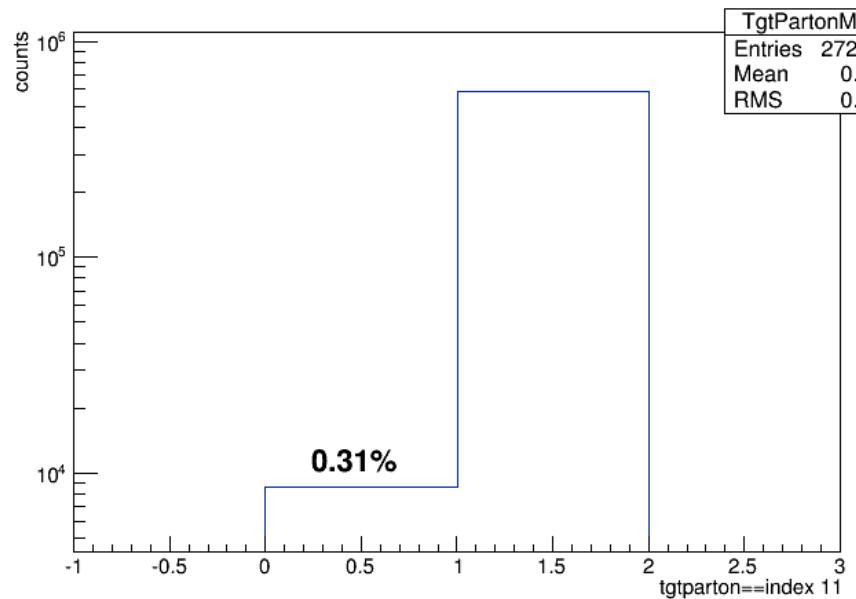
- The simulation shows the capability to measure the cross section for di-jet production, with high accuracy in a wide kinematic range at EIC
- First measurement of polarized photon PDFs with high precision
- Flavor tagging can also be applied in polarized case

Summary

- **In resolved processes, photon has a hadronic structure**
 - Di-jet produced in resolved and direct process can be well separated at EIC
- **Photon PDFs can be extracted by reconstructing x_γ**
 - x_{γ}^{rec} is correlated with input x_γ
 - We can effectively access the underlying photon PDFs by measuring di-jet cross section in quasi-real photoproduction at EIC
- **Jet from photon side goes more to negative rapidity**
 - Distinguish jets from beam side and target side
- **Flavor tagging can be achieved**

Back up

backup



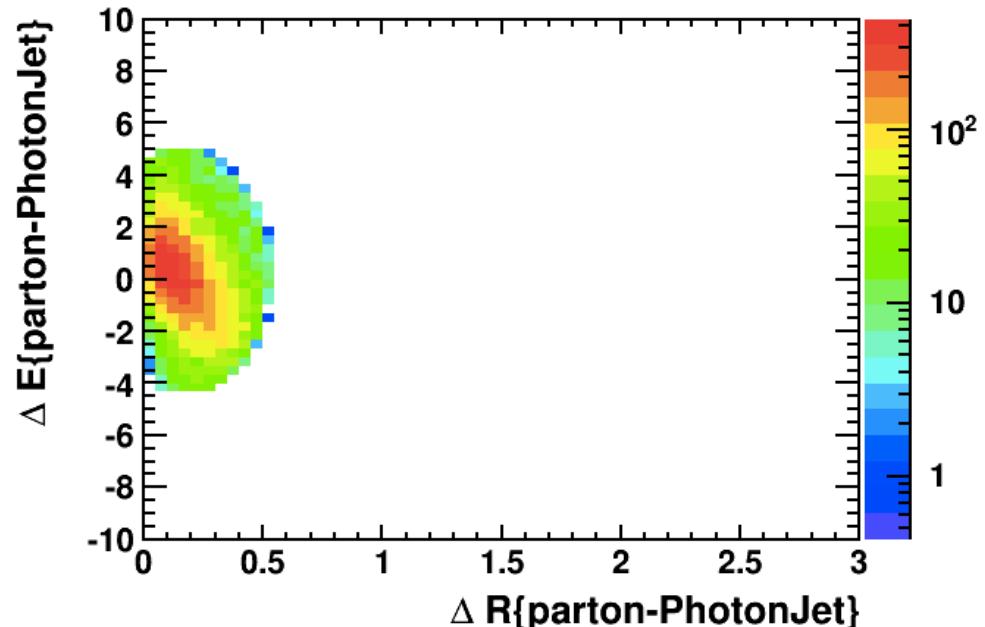
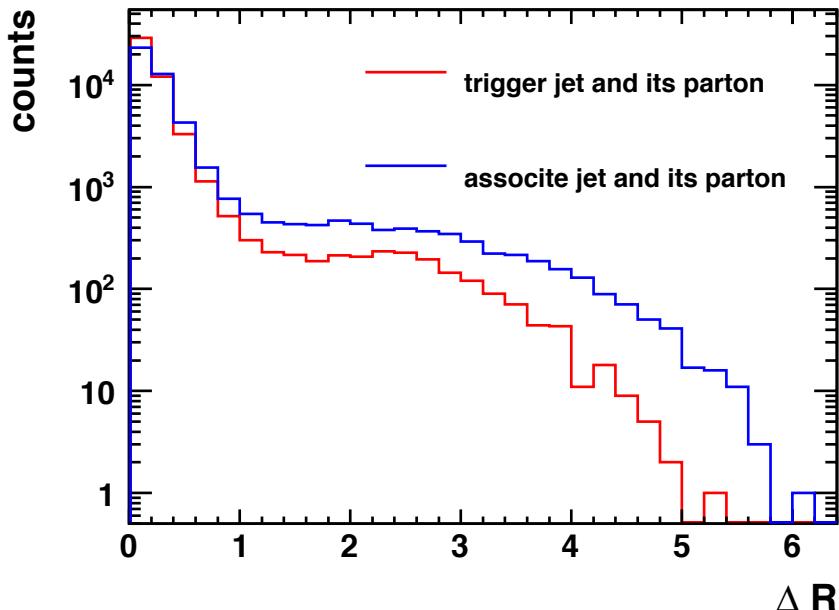
Flavor match: beamparton – index 9
tgtparton – index 10

How to match di-jet with two final partons

Geometric match:

$$\Delta R\{parton - jet\} = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

$$\Delta E\{parton - jet\}$$



beam parton

tgt parton



Two final
partons

POETIC7, Temple, Nov. 16

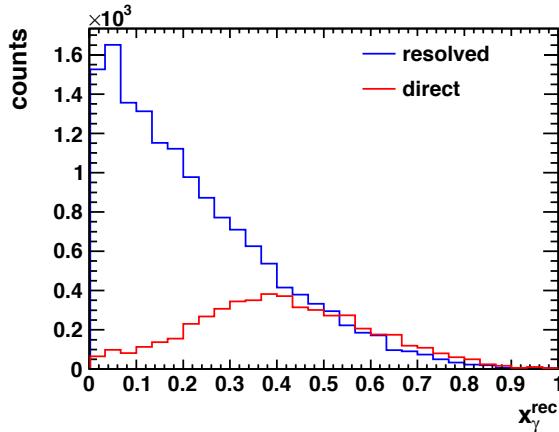
✓ match



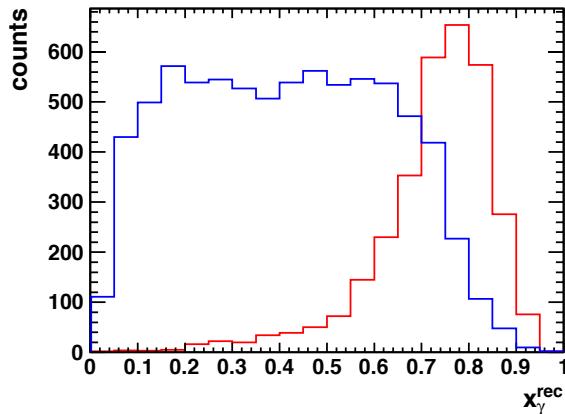
Di-jet

x^{rec}_{γ} separation

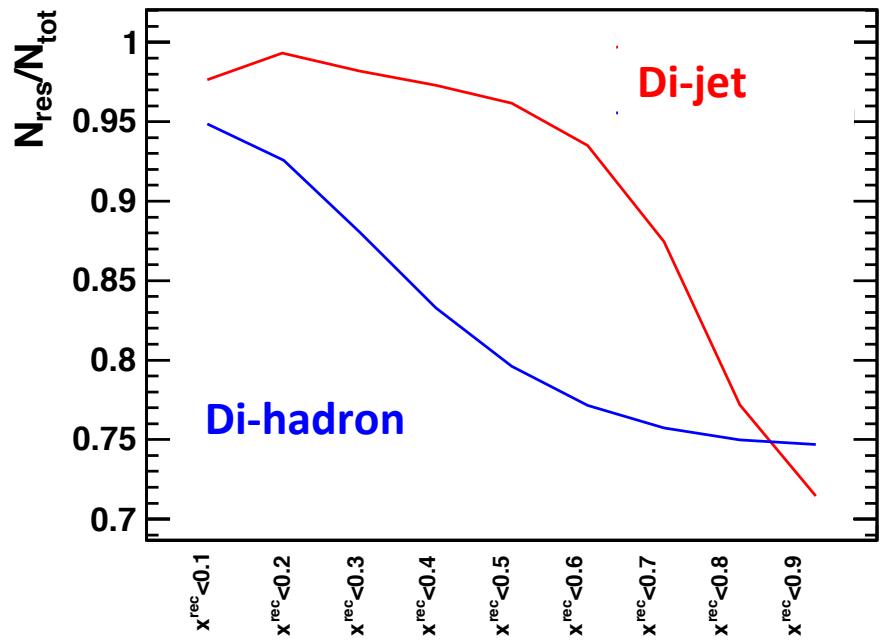
Di-hadron method



Di-jet method



If we choose different x^{rec}_{γ} cut, how well can we separate resolved/direct processes:

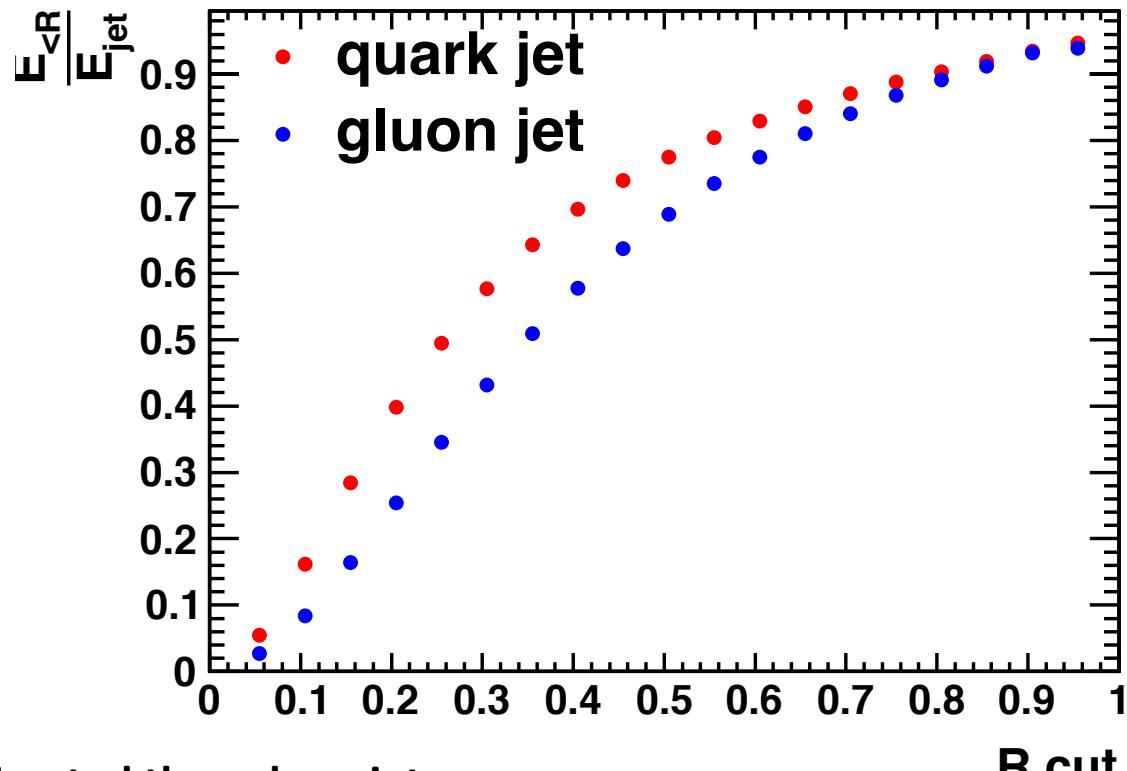
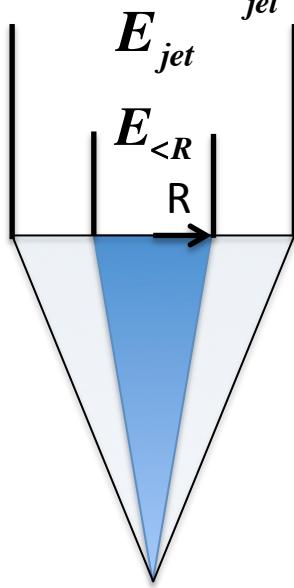


- Small x^{rec}_{γ} : mainly resolved contribution
- Large x^{rec}_{γ} : mainly direct contribution

- Di-jet method shows better separation of resolved and direct photon

Quark jet and gluon jet

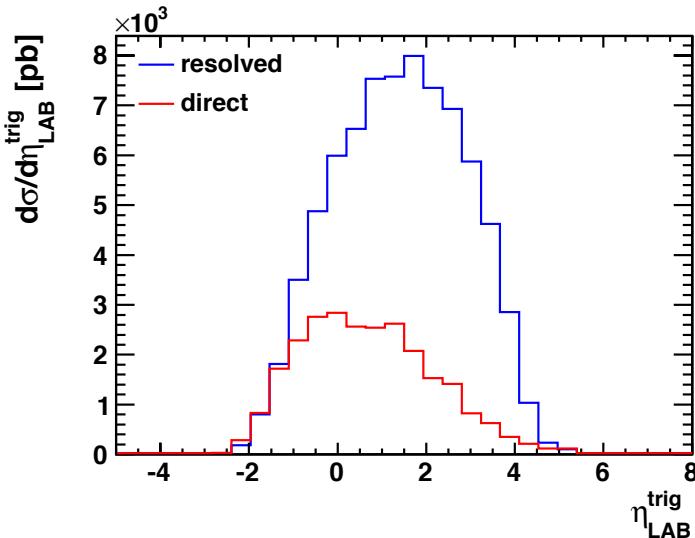
Jet profile: $\frac{E_{<R}}{E_{jet}}$



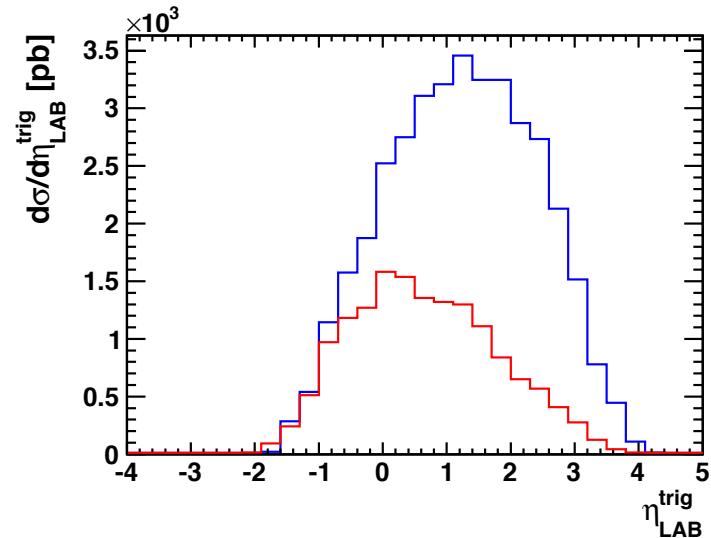
- Quark jet is more collimated than gluon jet
 - Choose a R cut with maximum difference value of jet profile, give possibility of types of jets

η_{LAB} separation

Di-hadron method



Di-jet method



- For both methods:
 - - At positive η_{LAB} , especially $\eta_{LAB} > 2$, the cross section is dominated by resolved process.

η_{LAB}^{asso} distribution of associate hadron/jet shows the same results